INFLUENCING FACTORS ON THE TEMPERATURE DEVELOPMENT IN CYCLIC COMPRESSIVE FATIGUE TESTS: AN OVERVIEW

EINFLUSSFAKTOREN AUF DIE TEMPERATURENTWICKLUNG BEI ZYKLISCHEN DRUCKSCHWELLVERSUCHEN: EIN ÜBERBLICK

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SUMMARY

Recent research in the project “Temperature and humidity induced damage processes in the concrete due to cyclic compressive fatigue loading” of the priority program SPP2020 focuses on the influence of humidity and temperature on the fatigue behaviour of concrete. It shows that the temperature development and the temperature height especially of HPC and UHPC depend on many influencing factors such as test frequency, amplitude, maximum grain size or humidity.

The present paper shows an overview of the literature on the various influencing factors on temperature development due to cyclic compressive fatigue loading and their effect on the fatigue resistance.

ZUSAMMENFASSUNG

Im aktuellen Forschungsprojekt “Temperatur- und feuchteinduzierte Schädigungsprozesse infolge zyklischer Druckschwellbeanspruchung” des Schwerpunktprogramms SPP2020 wird der Einfluss der Feuchtigkeit und der Temperatur auf die Betonermüdung untersucht. Es zeigt sich, dass die Temperaturentwicklung und die Temperaturhöhe vor allem von HPC und UHPC von vielen Einflussfaktoren wie zum Beispiel der Prüffrequenz, der Amplitude, des Größtkorns oder auch der Feuchtigkeit abhängen.

Die vorliegende Arbeit gibt einen Überblick der Literatur über die zahlreichen Einflussfaktoren auf die Temperaturerhöhung während zyklischer Druckschwellbeanspruchung und deren mögliche Auswirkung auf den Ermüdungswiderstand.

1. INTRODUCTION

The fatigue behaviour of concrete, especially of high-performance concrete (HPC), is very complex and even after many years of research, the design is still very conservative. Nevertheless, the fatigue behaviour of high-performance concrete becomes more important with respect to service life design. Mainly the influence of frequency, amplitude or humidity is investigated. Many investigations of concrete in cyclic compressive fatigue tests show a significant warming. Temperatures of up to T = 135°C have been documented in several cases [1]. Due to the dense microstructure of high-strength and ultra-high-strength concrete, the water vapour generated through high temperature cannot escape, which leads to increased pore vapour pressures [2]. The temperature gradient within the sample from the interior to the exterior is also said to have a damaging effect [2] and [3]. For this reason, there are ongoing research activities in the priority program SPP2020 „Cyclic deterioration of High-Performance Concrete in an experimental-virtual lab", funded by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) to investigate the influence of temperature on the fatigue behaviour of concrete. In the following, the general test procedure of cyclic compressive fatigue tests will be explained briefly. Thereafter, the influencing factors on the temperature development from the literature will be listed, explained, and compared with each other.

2. TEST SETUP OF CYCLIC COMPRESSIVE FATIGUE TESTS

The most fatigue tests in literature were conducted on a servo-hydraulic testing machine and were mostly operated load controlled, for example [3] and [4]. A typical testing machine and test setup are shown in Fig. 1. and Fig. 2. To minimise unintended bending of the test specimen due to imperfection of the plane-parallel top and bottom sides of the cylinders, a load transfer plate with a cup and ball bearing is used. During the fatigue tests, the number of load cycles, the applied loads and the deformation of the specimen are measured but unfortunately not always the temperature development. Temperature should always be measured, especially HPC and UHPC may reach very high temperatures.

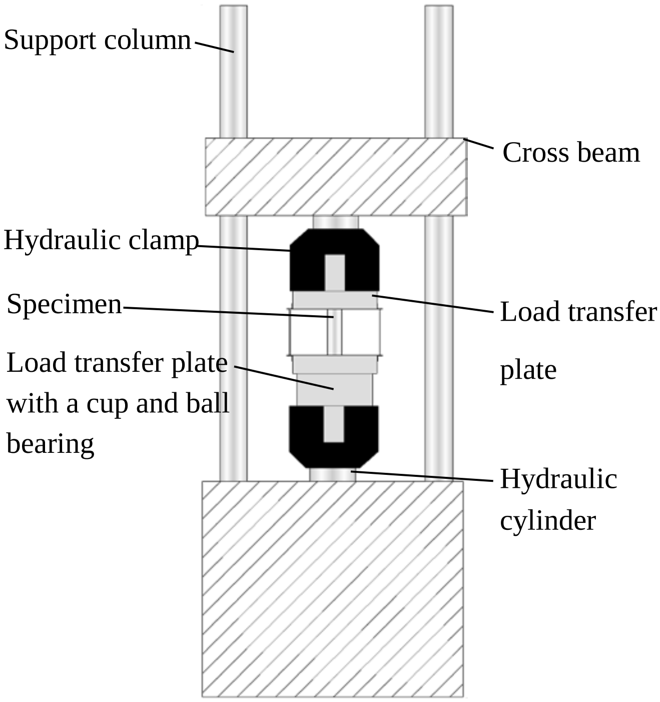

Fig. 1: Typical experimental set-up [4]

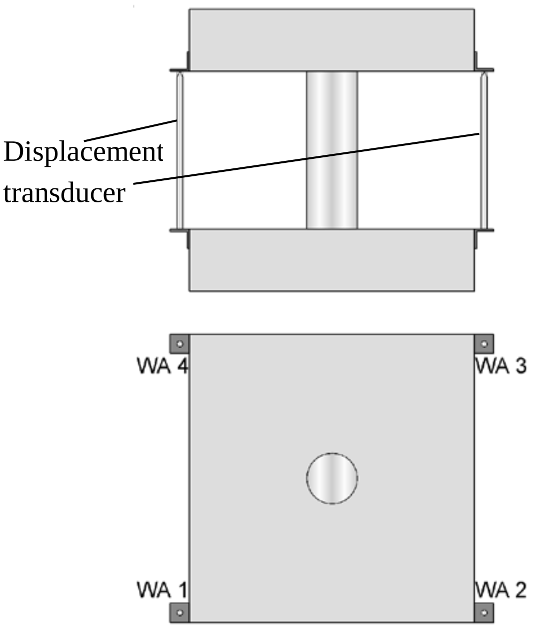

Fig. 2: Positions of the displacement transducers [4]

The temperature of the sample is not the same at all measuring points because the steel pressure plates at the top and bottom allow the sample to cool down faster. In addition to the room temperature, the temperature on the pressure plate which is connected to the hydraulic cylinder should also be measured, because additional heat is introduced into the concrete there. For detailed investigations it is also possible to place temperature sensors inside the specimen to measure not only the temperature on the surface (Fig. 3). Examples of the temperature sensor setup can be found in [2], [3], [4], [5] and [6].

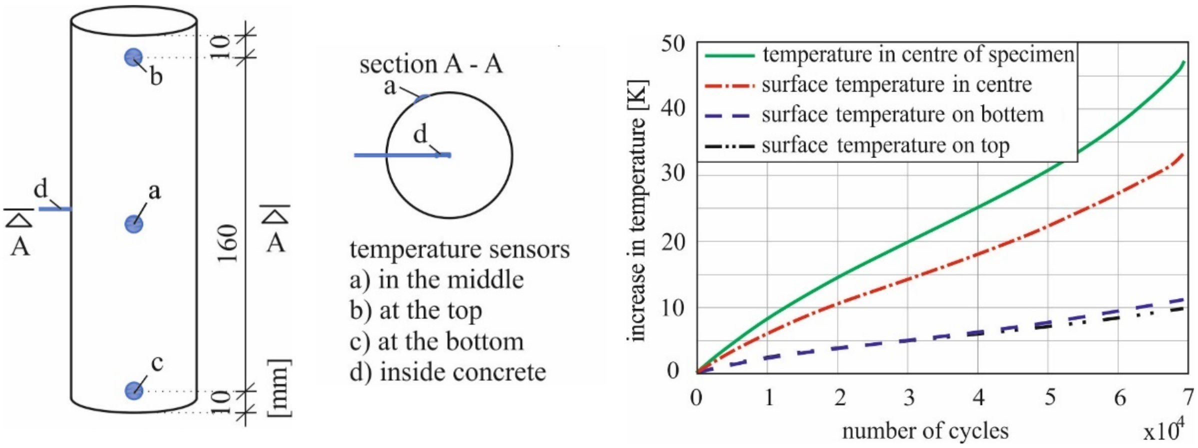

Fig. 3: Positions of the temperature sensors for fatigue tests [3] and temperature development of a test specimen of UHPC [3] and [5]

Fatigue tests under cyclic compressive fatigue loading are usually performed on cylindrical specimens with an h/d ratio of 3:1. This ratio creates an uniaxial stress state in the center of the sample [7] see Fig. 4. Common specimen sizes of 300/100 ([7]) or 180/60 ([9]) are often used. In tests with HPC or UHPC concretes, cylinders with a diameter of 60 mm are used because of the testing machine capacities.

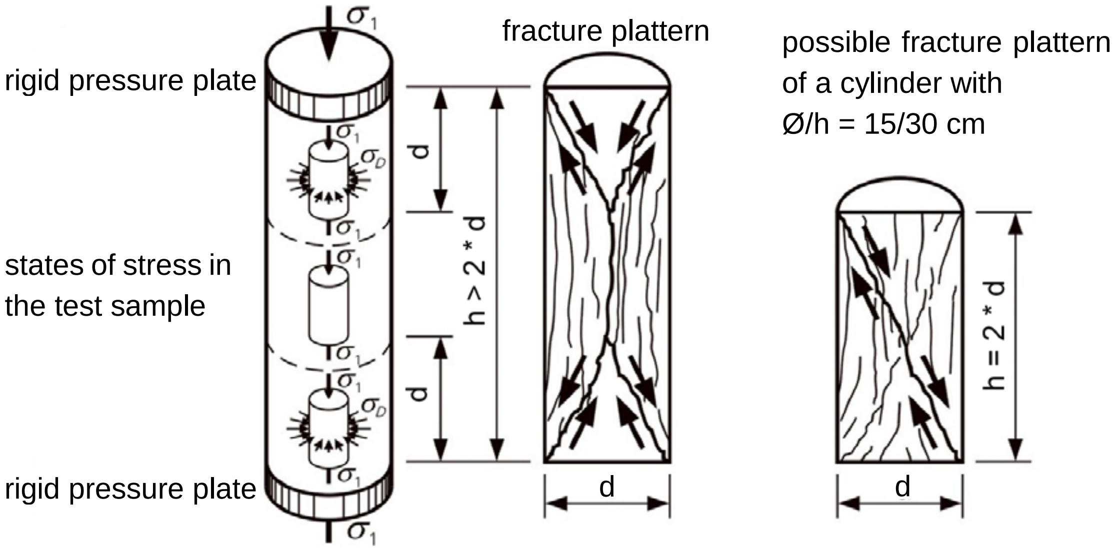

Fig. 4: Stress states on a cylinder during an uniaxial compression test according to [7] (translated)

3. INFLUENCING FACTORS

In the following, the individual influencing factors are named and shown based on the literature on how they affect the heating of the concrete during cyclic compressive fatigue tests.

3.1 FREQUENCY

In the literature, many investigations of the influence of frequency can be found. The influence of frequency is often linked to the related maximum stress level. An evaluation of the literature [10], [11], [12], [13] and [14] shows that there is an upper stress level of $S_o \geq 0.75$, where higher frequencies of loading also lead to higher numbers of cycles to failure. Below this level, higher frequencies tend to result in lower numbers of cycles to failure.

The influence of frequency on the temperature increase can also be found in the literature. Amongst others [2], [5], [15], [16], [17] and [18] have dealt with temperature development at different frequencies. As shown in [18], the temperature development of normal-strength concrete was investigated at two different frequencies (f_{P1} = 8.33 Hz, f_{P2} = 150 Hz). At the test frequency f_{P1}, no specimen heating could be measured, whereas the specimens under f_{P2} heated up to ΔT = 56 K. The results of the investigations of [17] also showed an effect of the test frequency on the temperature increase (see Fig. 5). In contrast to the specimens tested at f_P = 1 Hz, a strong temperature increase could be determined at each stress level in the specimens tested at f_P = 10 Hz. Thus in the studies of [6], this situation is instead investigated comparatively at a constant related upper stress level of S_O = 0.6 and with test frequencies of f_{P1} = 1 Hz, f_{P2} = 2 Hz, f_{P3} = 5 Hz and f_{P4} = 10 Hz. If the frequency is higher, the temperature increases faster and higher (see Fig. 6). Another group [5] carried out fatigue tests with different frequencies and observed the temperature development. At the test frequency of f_P = 20 Hz the specimen temperature increased by up to ΔT = 68 K, at f_P = 10 Hz by a maximum of ΔT = 40 K and at f_P = 3 Hz by a maximum of ΔT = 19 K. (See Fig. 5, chapter 3.2)

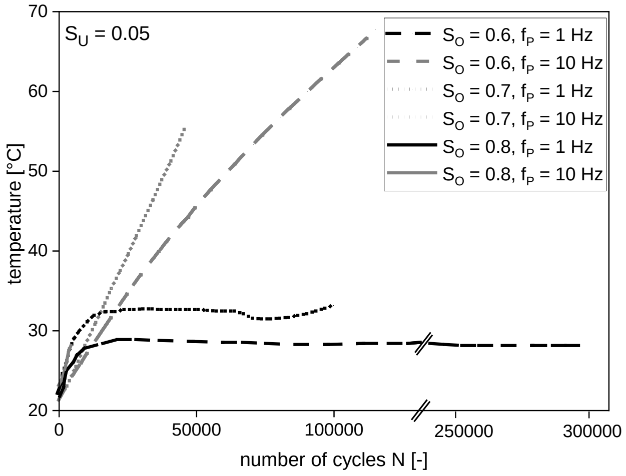

Fig. 5: Specimen heating for f_p = 1 Hz, 10 Hz according to [17] (translated)

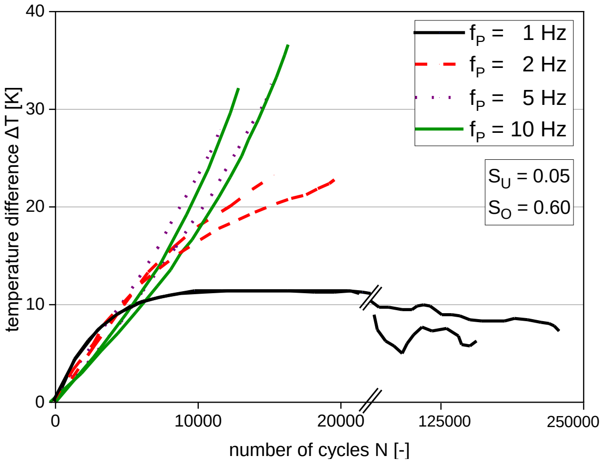

Fig. 6: Specimen heating depending on the test frequency according to [6] (translated)

It can be noticed that in general, higher frequencies at the same upper stress level lead to a higher heating during fatigue tests. As can be seen in the figures, both the absolute temperature increase and the heating of the test specimen depend on the frequency.

3.2 STRESS LEVEL

For the execution of fatigue tests, so-called Wöhler curves (S-N relations) are produced, whereby always either the upper stress $S_o = \sigma_o / f_{cm,cyl}$ or the lower stress $S_u = \sigma_u / f_{cm,cyl}$ is varied and the opposite value remains constant.

The influence of the stress level on the temperature development has already been recorded by many as [18] has already found that the temperature development depends on stress levels and amplitudes. Recent studies by [2] examined two high-strength grouting mortars compared at 1 Hz (green dotted) and 10 Hz (blue) as well as at two different stress levels. In Fig. 7 the two diagrams can be seen: on the left side with a stress level of $S_o = 0.85$ and on the right side with a stress level of $S_o = 0.60$.

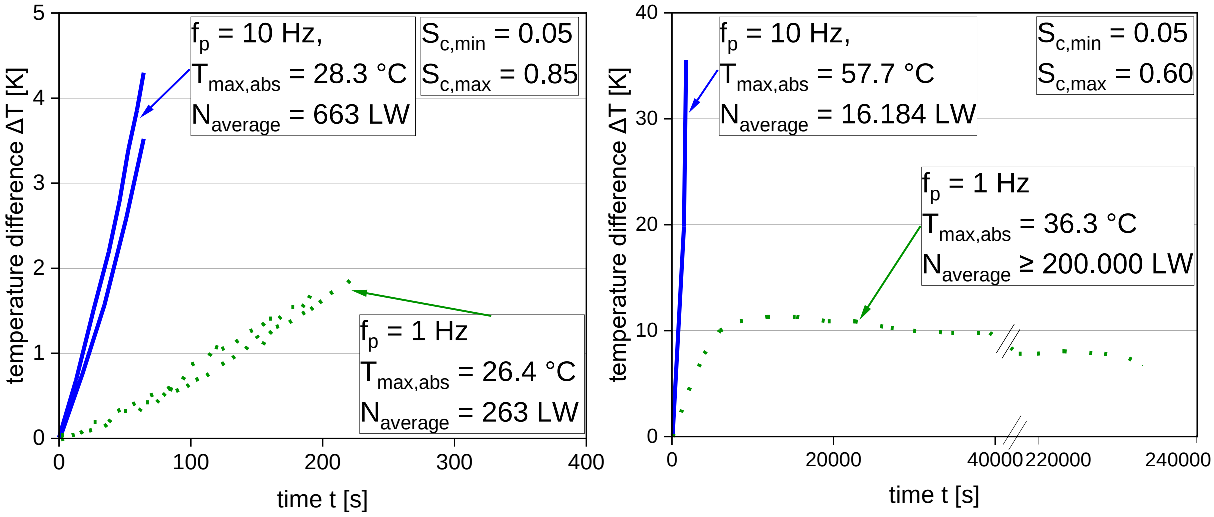

Fig. 7: Specimen's heating depending on the testing frequency and the load level according to [2] (translated)

It is noticeable that at a higher stress level the maximum heating is significantly lower than at a lower stress level. This effect has also been determined by [4]. This can be explaned by the different running times until failure. The test specimen with a lower stress level has a higher number of cycles to failure under cyclic compressive loading than a test specimen with a higher stress level. If the diagrams are compared separately, the increase in temperature development is significantly stronger with a higher frequency than with a lower frequency. This effect is investigated [5] on an UHPC with 3 Hz, 10 Hz and 20 Hz (see Fig. 8). In these investigations, the frequencies and the stress levels are varied. In contrast to the other investigations, the normalised minimum stress was $S_u = 0.10$. Each individual diagram shows the influence of three different stress levels at a corresponding frequency. It is noticeable that in all three diagrams the temperature development decreases significantly with decreasing stress level. [19] shows that with a constant upper stress, different lower stresses have an influence on the temperature development (Fig. 11, Chapter 3.4).

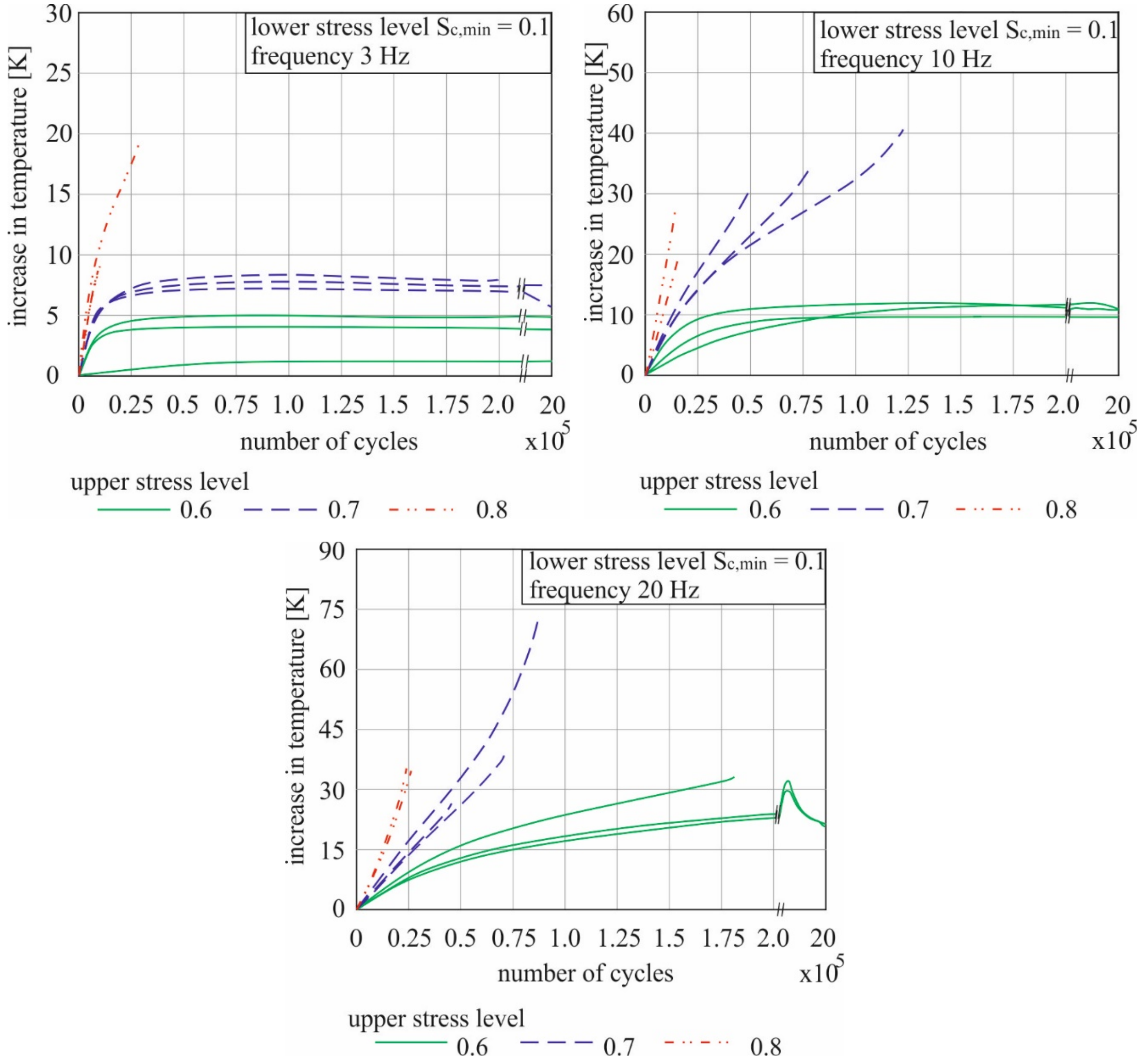

Fig. 8: Temperature development for 3 Hz, 10 Hz and 20 Hz on three stress levels [5]

The literature shows that the higher the related stress or stress amplitude, the faster the temperature of the test specimen rises. Although it cannot be generally said that higher absolute temperatures can be reached at higher stress levels, as the failure often occurs earlier [17].

3.3 HUMIDITY

Latest investigations have shown that the humidity of the concrete has a significant influence on the fatigue strength, especially with HPC and UHPC. The fatigue strength decreases with increasing concrete humidity [4], [6], [20], [21] and [22]. [23] showed with sound emission that the moisture in the microstructure causes additional water-induced damage mechanisms. In addition to the differences in the number of cycles to fail, the concrete humidity also has an influence on the temperature development. As a result, [4] showed that at the same relative stress level, the temperature development decreases with decreasing concrete humidity of the HPC (Fig. 9). [6] also found the same effect (Fig. 10); the samples dried at 35°C showed a slower temperature increase at both frequencies (10 Hz and 1 Hz) compared to the samples of normative storage. The maximum temperature that can be reached also seems to depend on the humidity [4]. In [1], it was shown that at the same maximum temperature of 135°C, the dried samples did not fail and achieved a higher number of cycles to failure compared to the samples with a higher humidity content. Both [1] and [6] led this additional or increased damage to the existing water which creates a vapour pressure in the concrete.

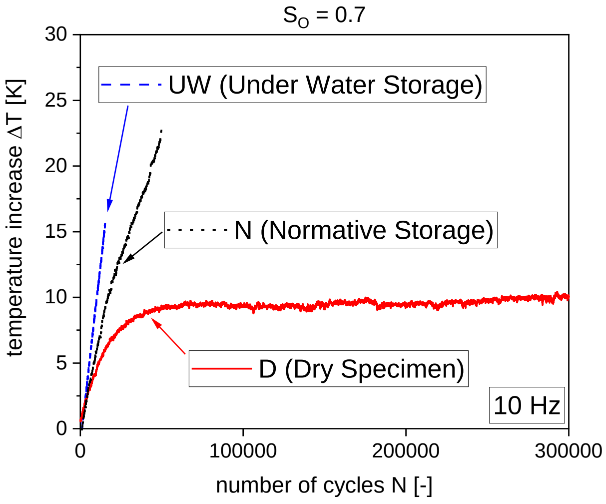

Fig. 9: Temperature increase of three different moisture contents at the load level S_o = 0,7 according to [4]

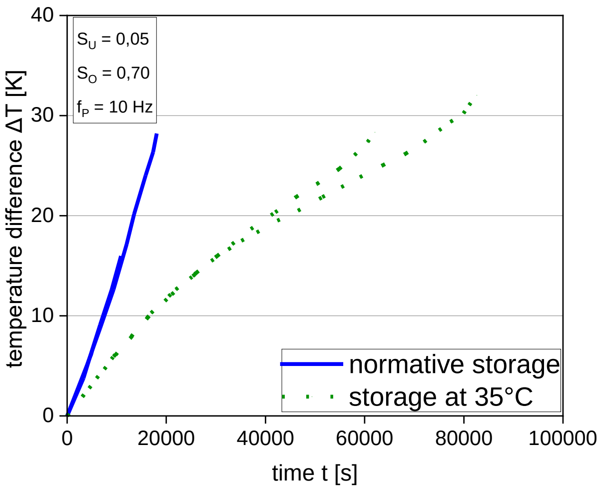

Fig. 10: Specimen heating as a function of moisture content [6] (translated)

3.4 COMPRESSIVE STRENGTH

In order to be able to apply the Wöhler curves (S-N relations) to the different concrete compressive strengths, the stress is related to the concrete compressive strength. As shown in [24], the influence of concrete compressive strength on the fatigue behaviour of HPC and UHPC in general has not yet been fully clarified and is one of the subjects of current research. This is important to study, since the Wöhler curves do not consider the compressive strengths. As a result, the reduction in fatigue design increases significantly with increasing strength ([25] and [26]). In addition to the influence of compressive strength on the Wöhler curves (S-N relations), the influence on temperature development was investigated in [19]. A normal concrete (C45/55), an HPC and a UHPC were investigated with a related upper stress level of S_o = 0.7 and two different related lower stresses (S_u = 0.05 and 0.10) at 10 Hz (see Fig. 11). It can be seen that the compressive strength has an influence on the increase in temperature as well as on the maximum achievable temperature. This is also a possible explanation why the UHPC fails earlier compared to the HPC (Fig. 11). According to [19], the influence of the compressive strength on the temperature development is shown by the fact that during the fatigue test, the specimens heat up faster with increasing compressive strength and reach a higher temperature.

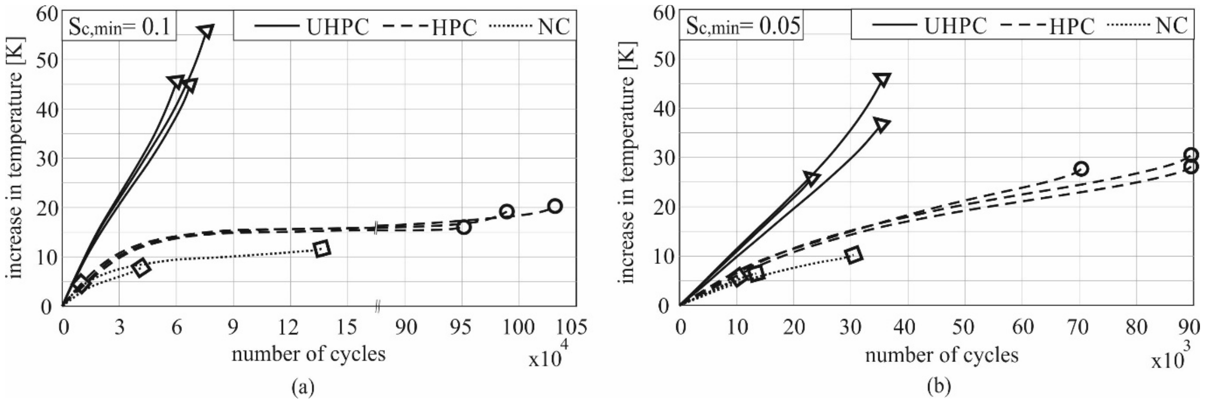

Fig. 11: Temperature development of all specimens (S_o = 0,7; fp = 10 Hz); Here: absolute heating on the surface [19]

3.5 SPECIMEN SIZE

The static compressive strength depends on the sample size and its diameter to height ratio ([27]). The topic of current research is to determine whether this effect also applies to the fatigue resistance. For this purpose, [28] have investigated two different concretes with different sizes (d/h = 60/180 and 100/300) as well as test frequencies and stress levels and found an influence. Fig. 12 shows that regardless of the frequency at the same stress level, the number of cycles to failure is higher with decreasing diameter. The effect was also attributed to the temperature development in respect of the ratio (A/V) of surface to volume. [21] also investigated this effect on cylindrical samples with a diameter of 60 mm (A/V = 0.08) or 100 mm (A/V = 0.05) and also observed the temperature development. He stored the specimens under water until the test. They were tested unsealed at 1 Hz and at a stress level of $S_o = 0.7$. The results of the investigations (Fig. 13) have shown that the specimens with a diameter of 60 mm (black dotted) compared to the specimens with 100 mm (black) initially have a similar temperature curve, but after only a few hundred load cycles the temperature increase decreases with the smaller diameters. Looking at the maximum temperature increase that has been realised, the samples with a diameter of 100 mm become significantly warmer. Accordingly, the specimen size also has an influence on the temperature curve.

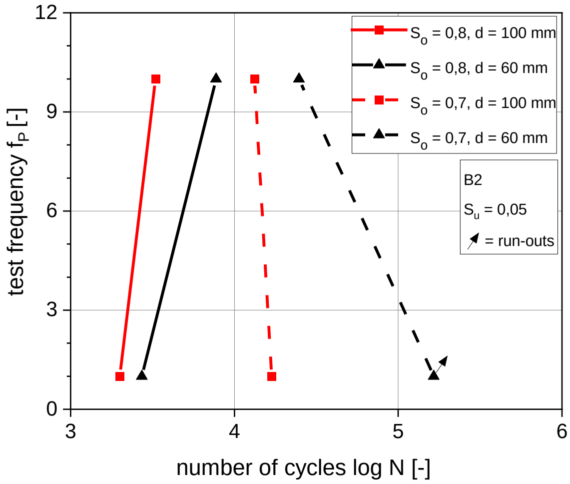

Fig. 12: Average values of the number of cycles to failure of concrete B2 for d/h = 60/180 mm and 100/300 mm, S_u/S_o = 0,05/0,80 and 0,05/0,70 according to [28] (translated)

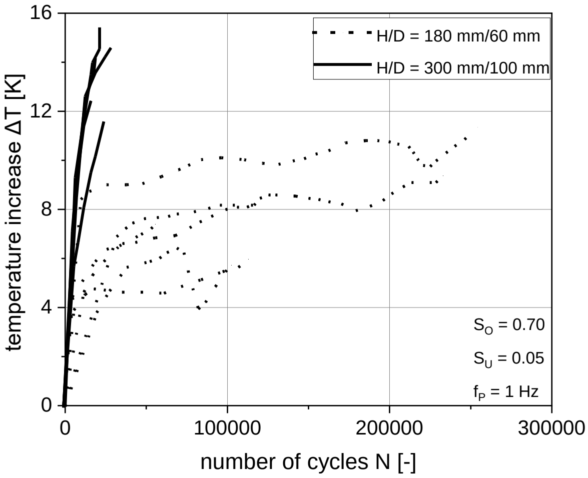

Fig. 13: Temperature increase of different specimen sizes according to [21] (translated)

3.6 MAXIMUM GRAIN SIZE

The fact that the largest grain size has an influence on the heating was investigated by [2], [5], [29] and [30]. In [2], three high-strength grouting mortars with different maximum grain sizes were tested. Fig. 14 shows the temperature increase over time during the fatigue process. The three grouting concretes were examined at a frequency of 10 Hz and a maximum stress of 75% and a minimum stress of 5%. Although all three mixtures approximate the same maximum temperature, they differ in their temperature increase. The sample with the grain size of 1 mm warmed up the fastest and required only 3000 load cycles until failure. The test with the grain size of 2 mm achieved twice the duration with around 6000 load cycles. The mixture with a grain size of 5 mm achieved a running time of about 15000 load changes, meaning five times longer than the mixture with the grain size of 1 mm. [2] shows that the smaller the largest grain, the stronger the specimen heating at the same stress level.

The same effect was also observed by [5] (Fig. 15). They investigated the heating of a UHPC with different maximum grain diameters ($d_{max.1} = 1$ mm, $d_{max.2} = 8$ mm). The specimens with the smaller maximum grain diameter also heated up faster than those with the larger one. [5] and [30] explained this effect by a larger internal friction surface between cement and aggregate in mixtures with smaller maximum grain size. Both [2] and [5] showed that failure occurred at the same temperature regardless of the size of the grain, so that a correlation between temperature and lifetime can be assumed.

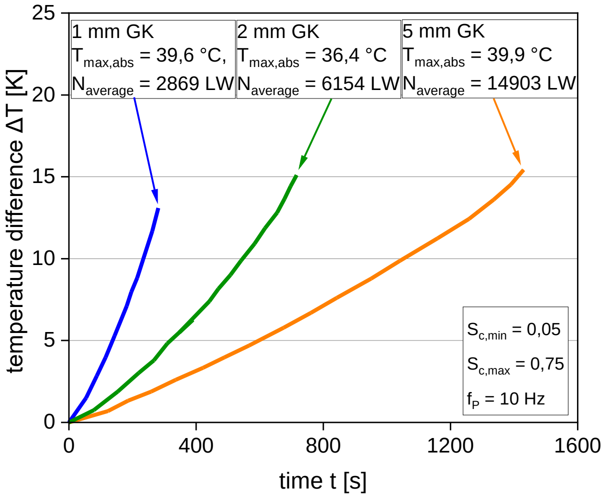

Fig. 14: Heating of the specimens depending on the maximum grain size [2] (translated)

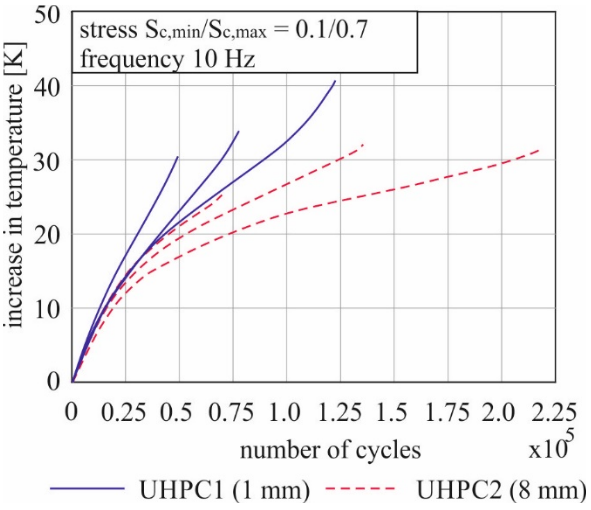

Fig. 15: Temperature development of specimens of UHPC1 and UHPC2 with different max. grain size [5]

4. CONCLUSION AND OUTLOOK

At current fatigue tests, attention is paid to the number of cycles to failure and the strain development. The temperature development should be analysed as it is another indicator of damage and may cause additional damage. This paper therefore takes a closer look at the different influencing factors on the temperature development of cyclic compressive fatigue loading tests. The influencing factors, their effect on temperature development and literature references are summarised in Table 1. In addition to the references mentioned in this paper, there are several others. Some of them can be found in [31].

In many investigations it has been proven that the heating caused by the cyclic swelling has an additional damaging effect. In tests in which the temperature rises more strongly or reaches a higher temperature, there is a tendency to fail earlier and achieve lower numbers of cycles to failure. Further research is necessary to understand the exact influence of temperature on fatigue behaviour. It is also not clear how far the temperature generated interacts with the concrete humidity. Heating can lead to drying of the concrete or to vapour pressures in the pore structure. Furthermore, the heating leads to an expansion of the concrete and thus to a reduction of the compression stress due to fatigue.

The influence of temperature on different concrete mixtures and their static compressive strength should also be considered more closely. The influence of the environmental temperature should also be investigated. A variation of the environmental temperature due to larger or smaller temperature differences can lead to larger temperature gradients within the sample.

Table 1: Overview of factors that influence temperature development

Influencing Factors	**Conclusion**	**References**
Frequency	higher frequencies produce a higher heating effect	[2], [5], [6], [15], [16], [17], [18]
Stress level	an increased related upper stress or stress amplitude leads to a faster temperature increase	[2], [4], [5], [17], [18], [19]
Humidity	a decreased concrete humidity leads to a slower heating and a lower maximum temperature	[1], [4], [6]
Compressive strength	a higher concrete compressive strength leads to faster heating and a higher temperature	[19]
Specimen size	a smaller diameter leads to a smaller surface to volume ratio (A/V) and thus to less heating	[21]
Maximum grain size	the smaller the largest grain, the stronger the specimen heating	[2], [5], [29], [30]

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